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ELECTROLYSIS OF SIMULATED LUNAR MELTS. Robert H. Lewis, David J. Lindstrom and Larry A. Haskin, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, Missouri 63130.

The Moon is our nearest source of extraterrestrial material, which we will need for expanding industrial activities in space early in the coming century. Our expanding industrial base will require increasingly large structures and increasing quantities of propellants in space. It takes only a small fraction as much energy to lift material from the Moon's surface to low-Earth orbit as to lift the same amount of material from Earth. Economy dictates that the Moon would be a cheaper source for constructional materials and propellants than Earth is if we can find needed raw materials there and develop sufficiently inexpensive methods to extract and use them.

We still do not know the full range of available resources on the Moon, but we do know that Moon, because of its dearth of water, free oxygen, and other gaseous materials, did not produce the same kinds of ores we are accustomed to using on Earth. Nevertheless, common lunar rocks are rich in oxygen, silicon, iron, aluminum, magnesium, calcium, and, in some cases, titanium. This is adequate for a considerable industry, provided that we develop appropriate technologies for extracting these elements.

Electrolysis of molten lunar soil or rock is, in principle, an attractive means of wresting useful raw materials from lunar rocks. It requires only heat to melt the soil or rock and electricity to electrolyze it, and both can be developed from solar power. Sunlight is abundant on the lunar surface half the time and in orbit nearly full time. There are no alternative sources of power present on Moon's surface or in orbit. Nor does Moon have water, or reducing agents such as coal, or expendable reagents as are available on Earth. To avoid the expense of importing large amounts of expensive materials, we must learn how to use sunlight and lunar rock as the basis for a constructional industry in space and to provide propellant and materials for life support.

In electrolysis, we pass electrical current between two electrodes. At one, the anode, a chemical element in ionic form is oxidized to elemental form. For example, oxygen bound in the silicate of lunar rocks would be oxidized to oxygen gas, a desirable product for propellant. Simultaneously at the other electrode, the cathode, a metallic ion, for example, iron ion, is reduced to the metallic form. Iron metal is also potentially a very useful product for construction in space. If iron metal were cheap, we could use it in space in ways in which we use other elements on Earth; iron might become the principal electrical conductor. Preliminary experiments show that both iron and oxygen can fairly easily be obtained by electrolysis of molten silicates, including simulated lunar lavas, on the small scale of laboratory conditions.

Lunar lavas have melting temperatures between 1100 and 1200 degrees Celsius, so we must electrolyze them at high temperature. If we raise the temperature to above 1535 degrees, the iron is produced in the molten state and sinks to the bottom of the electrolytic cell, from which we could tap it off for casting of parts, drawing of wire, and extrusion into beams or rods.

In order for electrolysis to be efficient, a high fraction of the electrical energy passing through the cell must yield the desired products by the oxidation-reduction process. Electrical current outside the cell occurs by transport of electrons through wires. Inside the cell, we need for it to occur mainly through transport of negatively charged ions toward

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the anode and positively charged ones toward the cathode. These ions are the silicate and metal ions of the molten rock. We need for the transfer of current between the melt and the external portion of the circuit to occur mainly by the oxidation-reduction processes. The oxidation of each oxygen at the anode releases two electrons to the electrode and its wire lead; reduction removes two electrons from the cathode and its wire lead and places them on an ion of iron. This enables the movement of electrons from the anode to the cathode through the wires of the outside portion of the electrical unit.

If the ions of the melt are too difficult to move, i.e., if the silicate melt has a low electrical conductivity (a high electrical resistance), a high voltage will be required to pass current through the melt. That would result in high energy loss as heat (analogous to the high-resistance wire in a toaster). Thus, we have to know the conductivities of common lunar materials when they have been melted. Conductivities are related to the mobilities of the individual ions that make up the melts. To gain a theoretical understanding of the contributions of the different ions of the melts, we must measure conductivities before there has been any significant migration of negative ions toward the anode and positive ions toward the cathode. That is because the net separation of charged ions increases the resistance of the melt relative to that of the perfectly mixed state. We make these measurements using alternating current, which rapidly changes the anode to a cathode and vice versa, then back again, many times. This switching precludes much separation of the ions. To simulate the condition of an electrolytic cell, we must make our measurements using direct current, so that the anode and cathode must retain constant identities and separation of ions does occur. We have to accept the increased resistance that this causes as part of the energy cost of doing electrolysis.

Our early experiments showed that rocks rich in the mineral ilmenite produced melts with much higher conductivities than did those low in ilmenite. We found that melts with a wide range of conductivities could be obtained just by controlling the amounts of ilmenite present. (Ilmenite has the chemical formula FeTiO_3 , and is thus rich in both iron and titanium.) Since ilmenite is plentiful on the Moon, this would seem to be a great convenience in design of cells for electrolysis. If the anode and cathode can be separated from each other by several centimeters distance, then a cell can be easily designed. However, as we increase the distance between them, the resistance to passing electrical current increases, and the higher the conductivity we need to maintain efficient use of electrical energy. Our ability to control conductivities turns out not to be as useful as desired, however, for allowing convenient design of electrolytic cells. It has been known for several years that some silicate melts have the properties of semiconductors; i.e., they allow some electronic conduction at even low voltages. The addition of ilmenite increased the semiconductivity of our simulated lunar rock melts. The direct passage of electrons through the melt in this manner does not contribute to electrolysis. It further heats the melt and ineffectively uses up part of the electrical energy.

To evaluate the magnitude of the problem, we measured the conductivities of the simple silicate, diopside, $\text{MgCaSi}_2\text{O}_6$. Then we added to it either iron oxide or titanium oxide to determine the effect on the conductivity. The titanium produced only the effect expected for ionic conduction. The iron, however, brought about substantial electronic conduction. The effect of the iron was so great that, if molten lunar rocks behaved in the same way, their electrolysis would be inefficient indeed! Fortunately, lunar

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rocks have more complex compositions than diopside, making electrolysis possible.

We measured the conductivities of simulated lunar lavas and the fractions resulting from ionic and electronic conductivities. The simulated basalt had an AC conductivity nearly a factor of two higher than that of diopside, reflecting the basalt's slightly higher total concentration of the 2+ ions Ca, Mg, and Fe that are the dominant charge carriers. Electrolysis experiments, in which the cathode was weighted to measure directly the efficiency of electrolysis, showed that electrolysis was about 30% efficient for the basalt composition. This value agrees with an estimate obtained from comparing AC and DC conductivities. Results of similar experiments with pure liquid ilmenite, FeTiO_3 , suggest electrolysis efficiencies of about 20%, while an equal mixture of basalt and ilmenite has an efficiency of less than 5%.

As a result of these experiments, we have shown that the fraction of ionic conductivity remains high enough that we can still expect to be able to electrolyze lunar lavas with reasonable efficiency to produce oxygen and iron. Cell design is more of a problem that we might prefer, however, because melts of only medium conductivity can be used. We now understand that iron is the principal contributor to the electronic conductivity and can seek ways of obtaining higher conductivities without using iron-rich minerals.